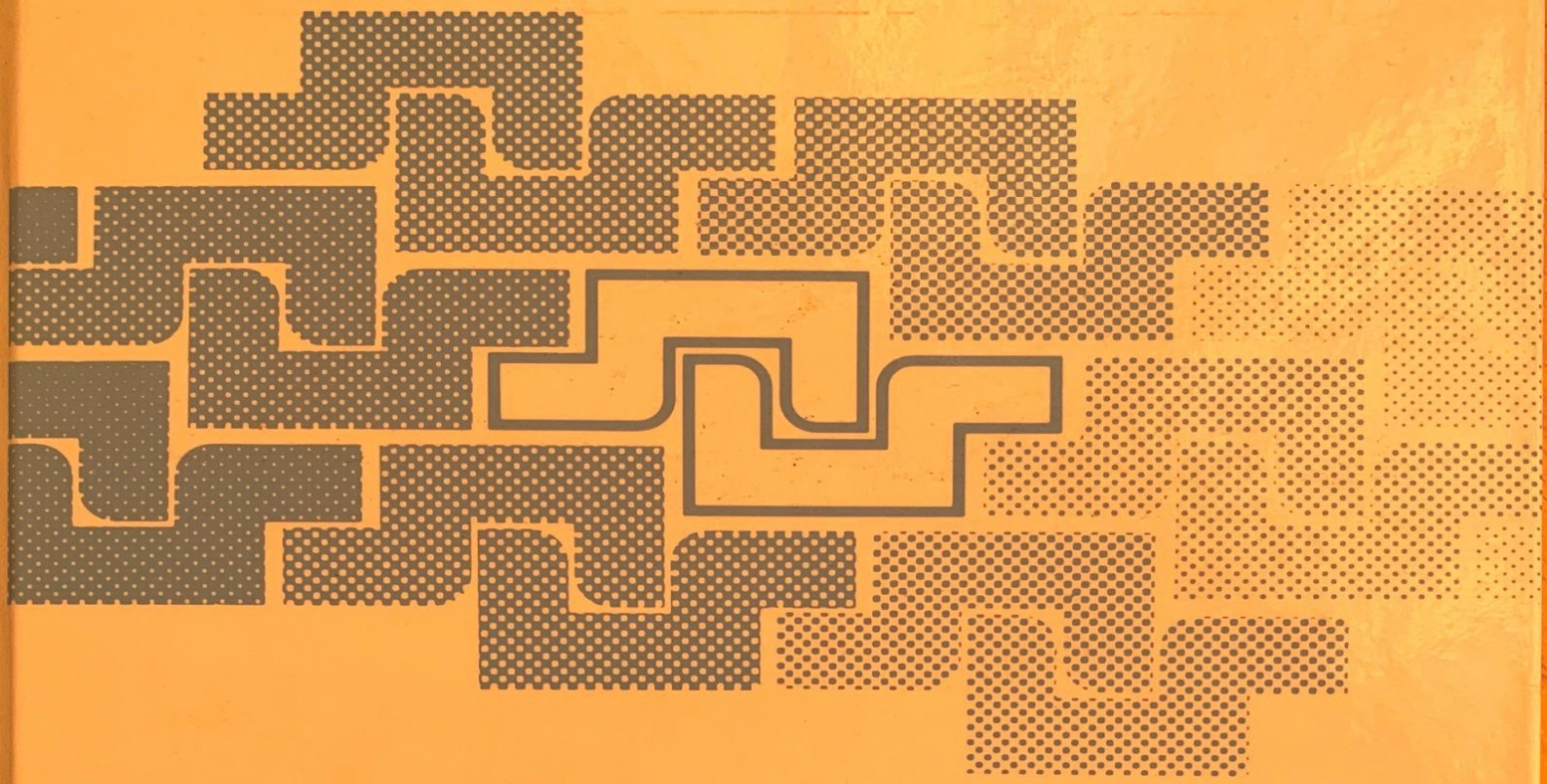

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LIGHT PROPAGATION IN POROUS MEDIA

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INTRODUCTION

Light propagation in composite media can be studied particularly conveniently in porous media. Such materials have the property that one of the components (the material in the pore space) can be chosen in a wide variety of ways. For example, it can be a suitable liquid, or a mixture of liquids. In addition, the composition can be a function of time. Thus, one can, by varying the composition of the pore space continuously, investigate a large number of different media in a single experiment.

In this paper, we discuss some basic concepts in light propagation in porous media, and illustrate by means of typical experiments how such media can be used conveniently for a range of both fundamental and applied investigations.

BASIC CONSIDERATIONS

In the study of light propagation in porous media, the most convenient quantity to measure is the transmission. Intuitively, one might expect this quantity to be immeasurably small in most porous media. Consider, for example, natural sandstone. This is a mechanical aggregate of irregularly-shaped quartz grains, and has porosity ϕ (i.e., pore volume divided by total volume) typically in the range 10% - 30%. Although the individual grains are transparent, a visual inspection of the composite rock suggests that it does not transmit light. Thus, it appears this most common naturally occurring optical composite is not amenable to study by visible light.

We have demonstrated recently, however, that when a sandstone is saturated with an appropriate fluid, there is a measurable transmission of visible light through macroscopic distances.[1] Our study, which was carried out in the short-wavelength limit ($\lambda << d$, where λ is the wavelength of the probing light and d is the typical grain size), leads to the following conclusions about the transmission T (Unless otherwise specified, the transmission T in this paper is defined as the total emergent power integrated over the exit face of a slab

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of porous medium corresponding to a collimated light beam incident normally at the entry face.):

(i). The smaller the contrast Δn between the refractive indices of the grains and the pore-filling fluid, the greater the transmission T.

(ii). The larger the grain size d (up to a certain limit), the greater the transmission T.

(iii). The more ordered the structure of the porous medium, the greater the transmission T.

It was also observed experimentally, and in numerical simulations, that the reflected power R at the entry face (the total power diffusely reflected from the entry face) shows the following correlation:

(iv). The smaller the grain size d or greater the contrast Δn, the greater the reflected power R.

Observation (i) suggests that porous media can be made to transmit visible light by introduction of an index-matching pore fluid. Observation (ii) suggests how the measurement of transmission can serve as a diagnostic probe of typical grain or pore size in a porous medium. Observation (iii) can be further developed through experiments in which a porous medium with an ordered structure can be made disordered by partial saturation with a contrasting pore fluid. Observation (iv) provides a qualitative understanding of the phenomenon of light-guiding in porous media.

DIFFUSIVE PROPAGATION IN POROUS MEDIA

Under certain circumstances, to be identified below, the propagation of light in porous media can be described by the diffusion approximation. Consider a monochromatic point source of light at the origin in a porous medium which is isotropic on a bulk scale. The average speed of light in the medium is $v = c/n$, where c is the velocity of light in free space and n is the appropriate effective refractive index of the medium.

We first assume there is no absorption in the medium. The propagation of light in the medium is then described by a photon "elastic mean free path" ℓ_{el}, defined by the condition that a photon travels a distance ℓ_{el}, on average, before being scattered. It has been shown that, approximately,[1]

$$\ell_{el} = \frac{4\epsilon_0^2 \ \zeta}{\langle(\delta\epsilon)^2\rangle \ln(2k^2\zeta^2)}, \qquad (1)$$

where ζ is an appropriate correlation length in the medium (assumed to be much smaller than the dimensions of the medium and much larger than the wavelength of light), ϵ_0 is the average dielectric constant of the medium, $\delta\epsilon$ is the dielectric contrast between the grain and the pore spaces, and $k = 2\pi\sqrt{\epsilon_0}/\lambda$ is the wave number. We expect ζ to be typically of the order of d. Using this fact, and neglecting logarithmic corrections, we find a simpler form of Eq. (1):

$$\ell_{el} \approx d\left[\frac{n\pi}{2\Delta n}\right]^2 . \qquad (2)$$

If we assume isotropic elastic scattering, then after N scatterings a photon will have been scattered, on the average, $N/3$ times in each of the three Cartesian directions. Thus, it will travel a rms distance $r = \ell_{el}\sqrt{N/3}$ in a time $t = N\ell_{el}/v$, or

$$r^2 = Dt \qquad (3)$$

where

$$D = \frac{v\ell_{el}}{3} \qquad (4)$$

represents the *photon diffusion constant*.

We expect to see diffusive behavior for sample thicknesses $L >> \ell_{el}$. In thinner slabs, the photons are expected to propagate ballistically. Another requirement for diffusive behavior is that $\ell_{el} >> \lambda$. If this condition is not satisfied, interference between the electric fields scattered from different scattering centers will influence the transmission. In summary, the conditions for diffusive propagation are

$$L >> \ell_{el} >> \lambda . \qquad (5)$$

Next, consider how this picture is altered by weak absorption. The absorption mean free path ℓ_{abs} is defined by the statement that a photon traveling a distance dx has a probability dx/ℓ_{abs} of being absorbed. Thus, the probability that a photon is not absorbed in distance x is $\exp(-x/\ell_{abs})$. Now, what is the probability that a photon has been absorbed by the time it travels a distance r from the origin? This takes a time r^2/D, so that the total path length traveled is vr^2/D. When this path length equals ℓ_{abs}, the probability that the photon has not been absorbed is 1/e. We call this distance r_{abs}:

$$r_{abs} = \sqrt{D\ell_{abs}/v} \quad . \qquad (6)$$

Unless r_{abs} is less than the sample thickness L, the transmission of light through a porous medium is little affected by absorption.

CONTINUUM VIEW OF LIGHT DIFFUSION: ANALOGIES TO FLUID FLOW

Just as light diffuses more easily in porous media with larger grain sizes, so also fluids flow more readily in porous media with larger grains (and hence, larger pores). This latter dependence can be seen from the following empirical relation for the permeability k_f of a porous medium towards fluid flow:[2]

$$k_f = C_0 \frac{\Phi^3}{S_0^2} \qquad (7)$$

where C_0 is an empirical constant, and S_0 is the specific surface area (the internal surface

area per unit bulk volume). Since $S_0 \alpha d^{-1}$, the permeability increases with increasing grain size.

The correlation between light transmission and fluid flow has recently been observed in experiments carried out on sandstones of various pore sizes.[1] In the following, we further explore the formal basis of this analogy between light transmission and fluid flow in porous media.

The permeability of a porous medium is defined by the Darcy equation:[3]

$$\vec{J}_f = -\frac{k_f}{\eta}\vec{\nabla}p, \tag{8}$$

where $\vec{J}_f$ is the fluid (mass) current density, η is the fluid viscosity, and p is the pressure.

In a diffuse photon field, the quantity analogous to the pressure is the diffuse intensity (or local energy density) U (see e.g., Ref. 4), which obeys the conservation law

$$\frac{\partial U}{\partial t} = -\vec{\nabla}\cdot\vec{J}_U - \alpha U + Q, \tag{9}$$

where $\vec{J}_U$ is the energy current density, α represents the fraction of the local energy density which is absorbed per unit time, and Q represents any sources or sinks of energy in a given volume. The current density $\vec{J}_U$ may be assumed proportional to the local energy density gradient:

$$\vec{J}_U = -D\vec{\nabla}U, \tag{10}$$

where D is the photon diffusion constant defined earlier. (The minus sign appears because the photons diffuse in the direction of decreasing photon number, or energy, density.) Combining the preceding two equations gives

$$D\nabla^2 U - \alpha U + Q = \frac{\partial U}{\partial t}. \tag{11}$$

We now consider some limiting cases. In the steady state, with no sources or sinks, we get

$$\nabla^2 U - K^2 U = 0. \tag{12}$$

We identify K with the quantity $1/r_{abs}$ defined earlier in Eq. (6), so the above expression becomes

$$K^2 = \frac{\alpha}{D} = \frac{3}{\ell_{el}\ell_{abs}}. \tag{13}$$

In absence of absorption, with no sources or sinks, we get

$$D\nabla^2 U = \frac{\partial U}{\partial t} \tag{14}$$

which is simply the diffusion equation. We can now rewrite Eq. (10) as

$$\vec{J}_U = -\frac{k_{opt}}{n}\nabla U. \qquad (15)$$

Thus, in analogy with Eq. (8),

$$k_{opt} = c\ell_{el}/3 \qquad (16)$$

is the "optical permeability" of the medium. The effective refractive index n is seen to be analogous to the viscosity η.

To explore the connection further, we examine the scaling of the optical permeability k_{opt} with grain size d. We compare this with the analogous scaling of the fluid permeability and the electrical conductivity of a porous medium consisting of non-conducting grains and a conducting pore fluid. Suppose that we expand such a medium isotropically, so that each linear dimension is increased by the same factor C. The electrical conductivity σ is scale-invariant, and remains unaffected by this transformation. The fluid permeability k_f will increase by a factor C^2, since the cross-section of each flow channel is increased by C^2, as is the Poiseuille flow through such a channel for a given pressure gradient and viscosity. Finally, the optical permeability k_{opt} is expected to increase by a factor C, since $k_{opt} \alpha \ell_{el}$ and we expect that $\ell_{el} \alpha C$. Summarizing the discussion, we have

$$\sigma(C) \ \alpha \ C^0 \qquad (17)$$

$$k_{opt} \ \alpha \ C^1 \qquad (18)$$

$$k_f \ \alpha \ C^2, \qquad (19)$$

and hence, for a given class of porous media,

$$k_{opt}^2/k_f = \text{const.} \qquad (20)$$

As one example of the above relationship, we may combine Eqs. (2), (7) and (16) to obtain (assuming spherical grains of diameter d)

$$\frac{k_{opt}^2}{k_f} = \frac{4C^2}{C_0\phi^3}\left[\frac{n\pi}{2\Delta n}\right]^4. \qquad (21)$$

CONNECTION TO ELECTRICAL CONDUCTIVITY FOR NON-TRANSMISSIVE GRAIN SPACE

In the context of the above discussion, porous media may be divided into two categories: (i) both the grain space and the pore space transmit light (e.g., sandstone, glass bead pack); and (ii) only the pore space transmits light. In the latter class, e.g., in some limestones, the grains appear milky white, indicating perhaps there is considerable scattering within a single grain so light transmission occurs essentially through the pore space.

For such media, the scaling law (Eqs. 17-19) may be made somewhat more concrete by resorting to suitable models. As an example, we may consider the "shrinking tubes"

model,[5] which was originally introduced in an effort to connect the electrical conductivity and the permeability of a porous medium. The model starts from a single cubic multi-dimensional network of pores, all of the same length a and initially of the same radius r_p. Then, at each stage i, a particular pore is selected at random and its radius is shrunk by a factor $x < 1$. After a number of shrinkages, this process leads to a very wide distribution of pore radii - probably consistent with real porous media. On this basis, it has been shown that the electrical conductivity σ and the fluid permeability k_f vary as power laws in the porosity ϕ:

$$\sigma \propto \phi^m \tag{22}$$

$$k_f \propto \phi^{2m} \tag{23}$$

where m is an index related to the shrinkage parameter x by

$$m = \frac{\ln(x^2)}{x^2-1} . \tag{24}$$

A similar argument can be made for the optical permeability. In a medium where the grain is full of internal defects that the photon mean free path inside the grain is very short (but still much larger than the wavelength), essentially all the light trying to enter the grain is reflected diffusely back into the pore space. Assume, for simplicity, the pore space is a regular cubic network of pores, each of length a and radius r_p ($a >> r_p$). Thus, a photon travels a distance of the order of r_p in the pore space before being reflected. Since the reflection is diffuse, the reflected ray may come off at any angle. Since the photon, on reflection, is equally likely to travel in either direction along the pore, there will be required, on average, about $(a/r_p)^2 = N$ reflections for a photon to travel the length a of a pore. The time required to do this is $\tau = (a/r_p)^2 \, r_p/c'$, where c' is the speed of light in the pore. When the photon emerges from this pore, it is equally likely to go in any of six directions. Thus, by the usual random-walk argument, the photon requires $3\nu^2$ time steps τ to travel ν pore lengths away from its starting point in the x direction. Putting all these estimates together, we find the time required to travel a distance $x = \nu a$ is about $t = 3x^2/r_p \, c'$ or $x^2 = Dt$ with $D = c'r_p/3$. Comparing this with Eq. (4), we find that the mean free path of a photon is of the order of r_p.

Hence, the photon conductance (i.e., photon energy current per unit intensity gradient) varies as r_p^3. (The extra factor r_p^2 comes from the cross-section, which converts a conductivity into a conductance.) By the same arguments used in the shrinking-tubes model, this leads to the relation

$$k_{opt} \propto \phi^{3m/2}, \tag{25}$$

and hence to the fact that the ratio

$$R = \frac{k_{opt}^2}{k_f \sigma} \tag{26}$$

is independent of the porosity ϕ. Hence, knowledge of any two of these three quantities can lead to an estimate of the third, as a function of ϕ, at least in this shrinking tubes model.

Finally, we examine the scaling of the optical permeability within the shrinking-tubes model. Suppose we expand each linear dimension of the medium by a factor C. This leaves

the porosity and the electrical conductivity unchanged, but increases k_f by a factor C^2 and k_{opt} by a factor C. Thus, R remains scale-invariant in this process.

CONFINEMENT OF DIFFUSE LIGHT IN HIGH PERMEABILITY CHANNELS

The formal analogy developed above between light transmission and fluid flow in porous media leads directly to the following experimentally testable prediction: In a porous medium made of grains of a given size, if there exists a channel of larger size grains, then light will tend to propagate preferentially through that channel (since it is the higher permeability path).

This prediction is tested qualitatively in the experiment of Figure 1 where, in a continuous medium made of "small" spherical glass beads (refractive index $n_{glass} = 1.52$[6]) there is a layer of an intermediate-sized beads and a layer of large beads. These two layers are interconnected. The largest beads correspond to the highest permeability, the smallest to the lowest permeability. The dissimilar bead layers are simply deposited one above the other, without there being any artificial interfaces. In order to achieve light transmission over the macroscopic distances of the experiment, the entire medium is saturated with water ($n_{water} = 1.33$[6]).

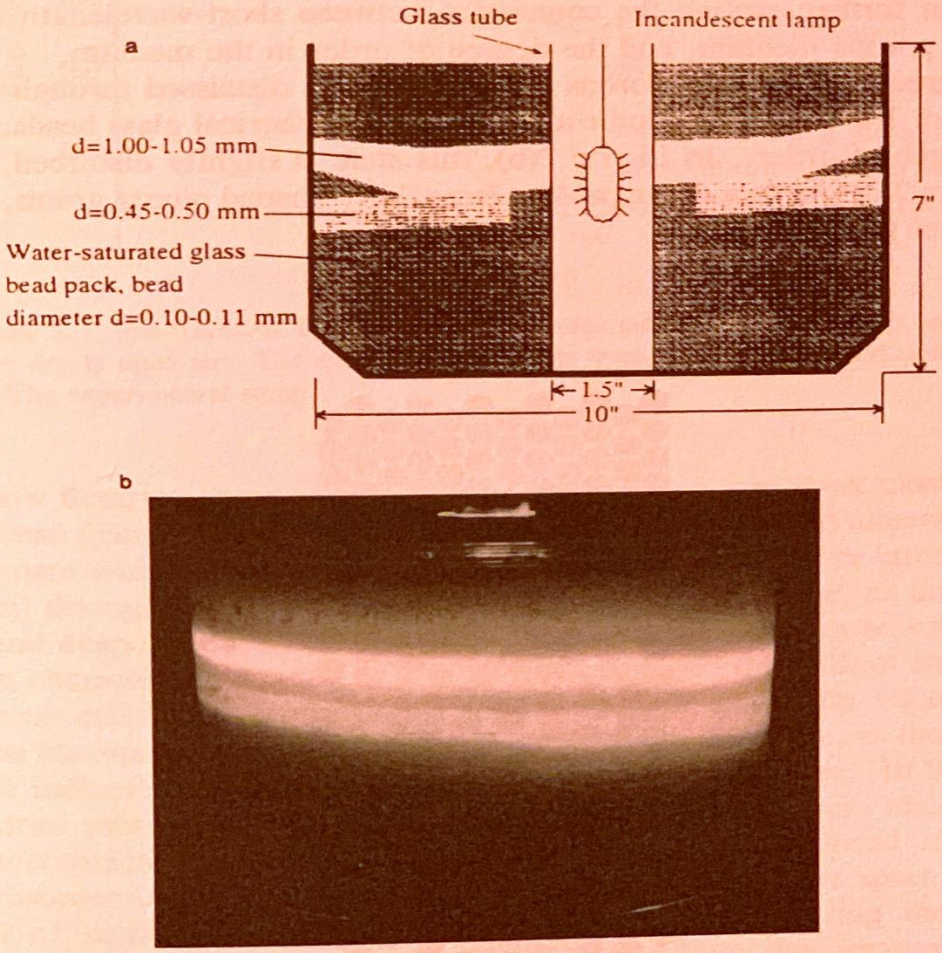


Figure 1. (a) A glass bead "reservoir" containing layers of different bead sizes, and an air-filled central glass "well" into which a light source can be lowered. The bead pack is saturated with water in order to achieve light transmission over macroscopic distances. (b) Photograph of the reservoir illuminated by a central light source (a 750 W tungsten-halogen lamp).

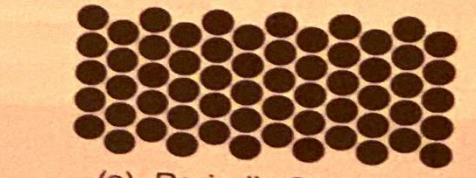
The results of the experiment [Figure 1(b)] illustrate the analogy: the maximum light transmission occurs through the layer with the largest bead size (the highest permeability layer). A somewhat weaker transmission occurs through the layer with the intermediate bead size (the intermediate permeability layer). Very little transmission occurs through the medium with the smallest beads, or the lowest permeability medium. Note how the light passes from the high permeability channel through to the intermediate permeability channel. (There is no direct path to the latter channel from the source.)

Apart from the analogy to fluid flow, the above experiment also illustrates the phenomenon of light-guiding in a porous medium. This will be discussed more generally in a following section.

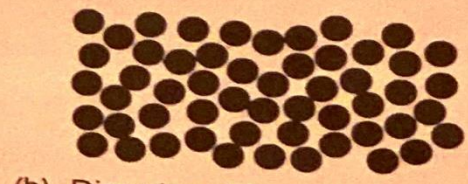
MORPHOLOGICAL VIEW OF LIGHT DIFFUSION: ORDER-DISORDER TRANSITIONS

It was mentioned earlier that, in the short-wavelength limit, the transmission T is larger through an ordered medium than through a disordered medium, all other things being the same. This behavior is seen in transmission through close-packed aggregates of spherical glass beads and though such packs of irregularly-shaped quartz grains of comparable size. The former exhibit a far greater transmission. We now describe numerical simulations and experiments that further explore the connection between short-wavelength transmission of light through a porous medium, and the degree of order in the medium.

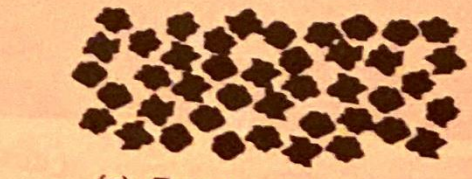
The degree of order in a porous medium may be discussed through the sketches in Figure 2. Figure 2(a) shows a periodic arrangement of spherical glass beads, and represents the highest degree of order. In Figure 2(b), this state is slightly disturbed, creating some disorder. Figure 2(c) shows a dense pack of irregularly-shaped quartz grains, and represents a structure of yet greater disorder.



(a) Periodic Structure



(b) Disordered Periodic Structure



(c) Random Structure

Figure 2. Illustration of ordered and disordered structures in porous media.

The ideal arrangement in Figure 2(a) is difficult to materialize in practice. However, the difference in transmission between the cases in Figures 2(a) and 2(b) can be studied by means of numerical simulation calculations such as described in Ref. 1. It is found that the transmission T for the case (b) is higher. Thus, near perfect order, transmission may actually increase with the introduction of disorder, depending on how the disorder is created.

The difference between the cases in Figures 2(b) and 2(c) can be studied conveniently through experiments, such as shown in Figure 3, which also serve to investigate the effect of *time-dependent* disorder in each individual medium.

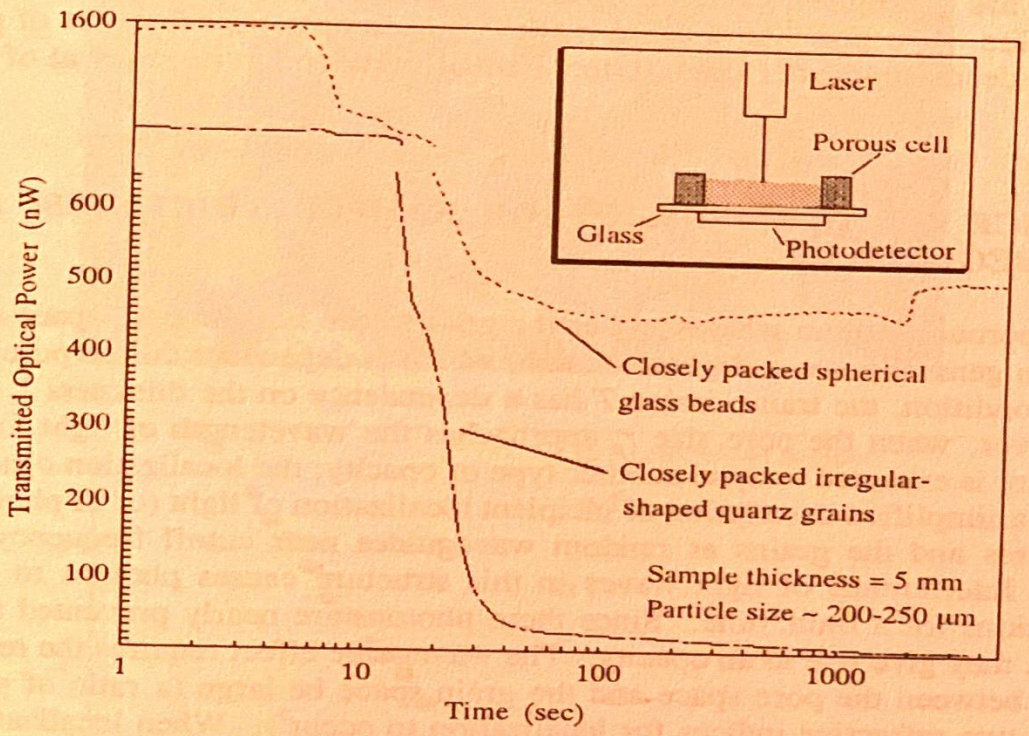


Figure 3. Time-traces of the transmission through toluene-saturated glass bead and sand grain packs, as they dry in open air. The experiment proceeds from the fully saturated state to the fully dry state. Inset: The experimental setup.

We now describe these experiments in detail. A 5 mm thick close-packed layer of glass beads (bead diameter = 250-300 μm) is kept fully immersed in toluene ($n_{toluene} = 1.49$[6]) in a compartment with porous wall. The transmission T of a He-Ne laser beam (red light; $\lambda = 0.63$ μm) through the layer is monitored as a function of time, as the bead pack dries through natural evaporation. The behavior of the transmission can be understood through the following characteristic stages. During the first stage, the bulk of the liquid is drawn into the porous cell wall, leaving the remaining liquid as a film adhering to the bead surfaces. The transmitted power decreases rapidly during this stage, as the contrast between the refractive indices of the beads and the pore space grows larger. In the next stage, the pore space dries more or less uniformly throughout the bead pack, and the transmission decreases monotonically but more slowly. We attribute the reduced transmission to an increase in disorder in the form of air/liquid interfaces in the pore space which contribute a great deal of surface area from which to scatter light. During the final stage, the transmission increases and then levels off. We attribute this increase to the gradual disappearance of the air/liquid interfaces (which, of course, must be absent when evaporation is complete), and hence to a transition from a disordered state back to a somewhat more ordered state.

Figure 3 also shows the results of the same experiment carried out in a close pack of irregularly-shaped sand grains (made of mineral quartz, $n_{quartz} = 1.55$[6]) with a size range and refractive index similar to the glass beads. Since the sand pack, unlike the bead pack, is highly disordered to begin with, the removal of a small additional disorder (in the form of air/liquid interfaces) at the last stage does not appreciably increase the transmission. Hence, in contrast to the glass bead pack, the transmission through the sand pack decreases monotonically with time to its fully dry value. It is also noted that in the fully-saturated or fully-dry state, the glass bead pack has a far greater transmission than the sand pack.

In summary, of the three configurations in Figure 2, the slightly disordered configuration has the highest value of the transmission T, and the random configuration has the lowest value. It is possible to cause a porous medium to pass to states of progressively increasing or decreasing order through the gradual introduction or removal of a pore fluid.

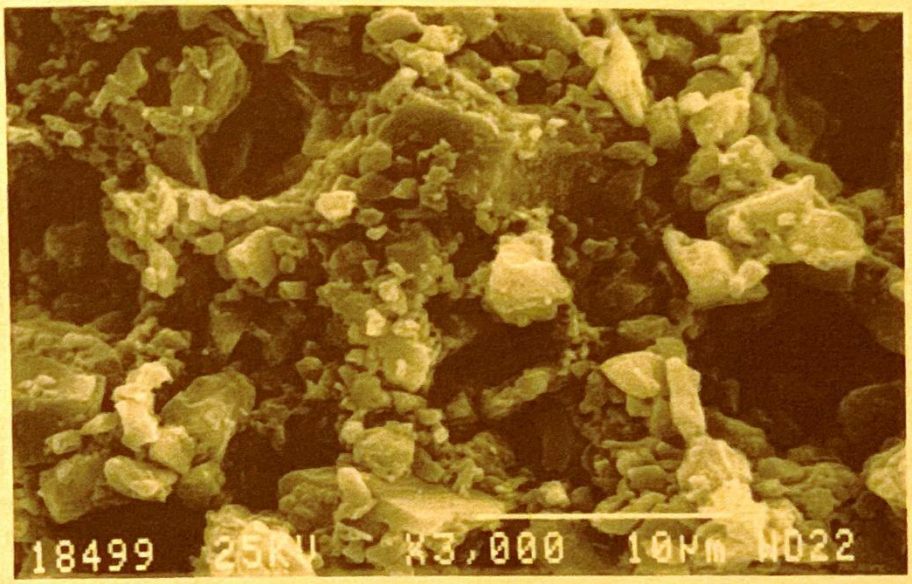
DEPENDENCE OF TRANSMISSION ON SAMPLE THICKNESS: STUDY OF OPACITY REGIMES

In a porous medium where neither the grain space nor the pore space absorbs light, the opacity is generally due to light diffusion, which is dependent on the pore size-scale r_p. Under this condition, the transmission T has a dependence on the thickness L of the sample slab. However, when the pore size r_p approaches the wavelength of light in a disordered medium, there is expected to arise another type of opacity: the localization opacity (see e.g., Ref. 7). In a simplified description of incipient localization of light (or of photons), we may view the pores and the grains as random waveguides near cutoff frequency and random resonators. Interference of light waves in this structure causes photons to be trapped in certain locations for a finite time. Since these photons are nearly prevented from reaching the detector, they give rise to an opacity. The waveguide effect requires the refractive index contrast Δn between the pore space and the grain space be large (a ratio of perhaps 2 to 3 between the two refractive indices for localization to occur[7]). When localization opacity is superimposed on diffusion, we expect the dependence of T on L to change. For this, and other reasons, it is useful to study the dependence of transmission on the sample thickness.

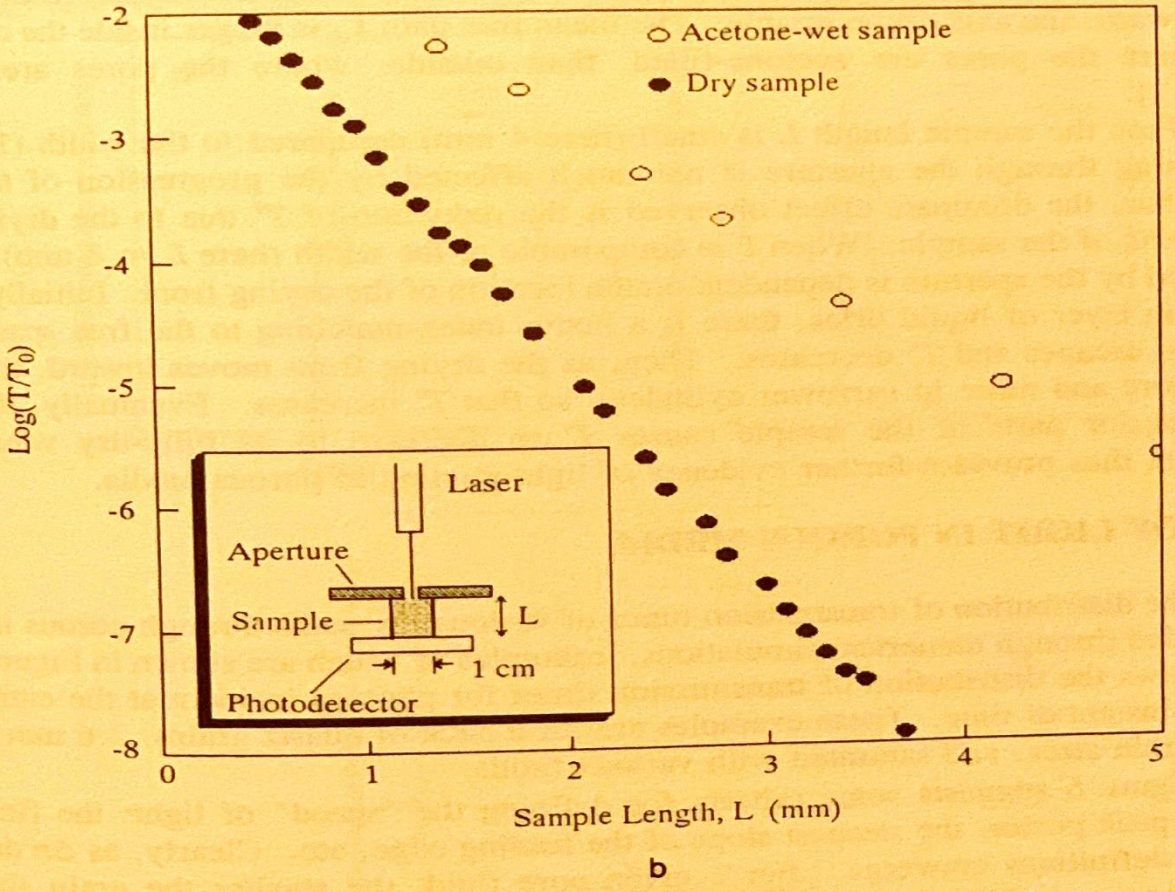
For this experiment we look for a porous medium with pore sizes comparable to the wavelength of visible light. Such a medium is natural chalk, or porous calcite. Calcite is optically birefringent,[8] with principal indices of refraction 1.49 and 1.67. Thus, for air-filled pores, the refractive index ratio is about 1.5 which may or may not be large enough to cause localization. Since natural chalk is often heterogeneous on a millimeter scale, and may contain impurities, a preferable alternative for this experiment is the familiar chalkboard chalk [Figure 4(a)]. We note that the pore sizes here bracket the wavelength of red light, 0.63 μm.

Figure 4(b) shows the dependence of the transmission T (normalized to the incident optical power T_0 ; $T_0 = 10$ mW) on the sample thickness L for dry chalk. The graph indicates a dependence of the type $T \propto T_0 \exp(-\chi L)$, where the slope χ of the graph is an opacity-like quantity. This is indicative most likely of a single source of opacity (i.e., diffusive opacity) in the range of the measurement. The lowest power measured is 1.0 nW, below which we reach the noise floor of the measurement setup.

For comparison, we also show in Figure 4(b) the results for chalk samples soaked (i.e., nearly fully saturated) in acetone ($n_{acetone} = 1.37$[6]). The exponential dependence is again observed. As expected, the transmission is higher, and χ is lower.



a



b

Figure 4. (a) SEM photograph of the pore structure of chalkboard chalk, with 10 μm scale shown. (b) The transmission as a function of the sample length for dry and acetone-wet samples of chalk. Inset: The experimental setup.

LIGHT-GUIDING IN POROUS MEDIA

The earlier observation of light confinement in high permeability channels is in fact a result of a "reflection" of diffuse light at the interface between two porous media with different values of the photon mean free path ℓ_{el}. As is evident from Eq. (2), this difference can arise due either to a difference in the pore/grain sizes (as in the above example) or to a difference in the pore fluid (as in the example below). Before describing an experiment that provides evidence for the latter case, we present a simple qualitative argument to support the concept of light-guiding in a porous medium.

We consider an imaginary surface dividing two porous media with mean free paths ℓ_{el1} and ℓ_{el2}, with $\ell_{el1} > \ell_{el2}$. Then, by observation (iv) mentioned at the outset, a photon starting at this surface and traveling into Medium 2 has a greater probability of being reflected into Medium 1 than *vice versa*. The overall effect of this is to cause confinement of light in Medium 1. A formal theory of light-guiding in porous media can be developed from these initial considerations.

Figure 5 shows the experiment supporting the idea of light-guiding in an initially homogeneous porous medium where a difference in ℓ_{el} is created by having different pore fluids. The sample is again chalkboard chalk, but now a portion T' of the transmitted light T is observed through an aperture. Initially, the sample is fully saturated with acetone. It is then allowed to dry by natural evaporation. The top and the bottom faces of the sample are sealed against evaporation with transparent seals, so a cylindrical drying front gradually moves towards the axis of the sample. The mean free path ℓ_{el} is longer inside the cylindrical front where the pores are acetone-filled, than outside, where the pores are air-filled [Cf. Eq. 2].

When the sample length L is small (here 4 mm) compared to the width (1 cm), the light passing through the aperture is not much affected by the progression of the drying front. Thus, the dominant effect observed is the reduction of T' due to the drying of the central parts of the sample. When L is comparable to the width (here $L = 8$ mm), the light intercepted by the aperture is dependent on the location of the drying front. Initially, as soon as the skin layer of liquid dries, there is a better index-matching to the free space so that more light escapes and T' decreases. Then, as the drying front moves inward, the light is guided more and more in narrower cylinders, so that T' increases. Eventually, the drying of the interior parts of the sample causes T' to decrease to its fully-dry value. This experiment thus provides further evidence of light-guiding in porous media.

SPEED OF LIGHT IN POROUS MEDIA

The distribution of transmission times of various ray paths through porous media has been studied through numerical simulations,[1] examples of which are shown in Figure 6. The figure shows the distribution of transmission times for photons incident at the entry face at the same instant of time. These examples are for a pack of quartz grains, 2.6 mm thick, of various grain sizes, and saturated with various fluids.

Figure 6 suggests some criteria for defining the "speed" of light: the first arrival time, the peak power, the steepest slope of the leading edge, etc. Clearly, as Δn decreases, all these definitions converge. For a given pore fluid, the smaller the grain size d, the smaller the speed of light. Referring back to observation (i) mentioned at the outset, we find that smaller the speed of light, the smaller the transmission T. In this way, the speed of light and the transmission in porous media are linked. A detailed analysis of the speed of light in random media may be found in Ref. 9.

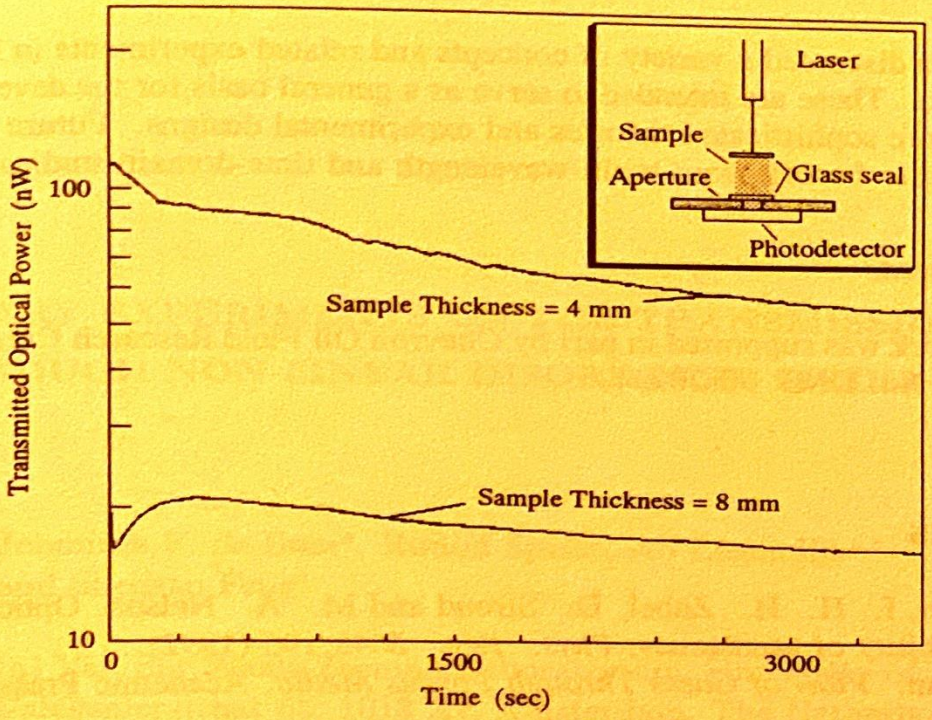


Figure 5. Time-traces of the transmission through acetone-saturated samples of chalk as they dry from the fully saturated state to the fully dry state. Inset: The experimental setup.

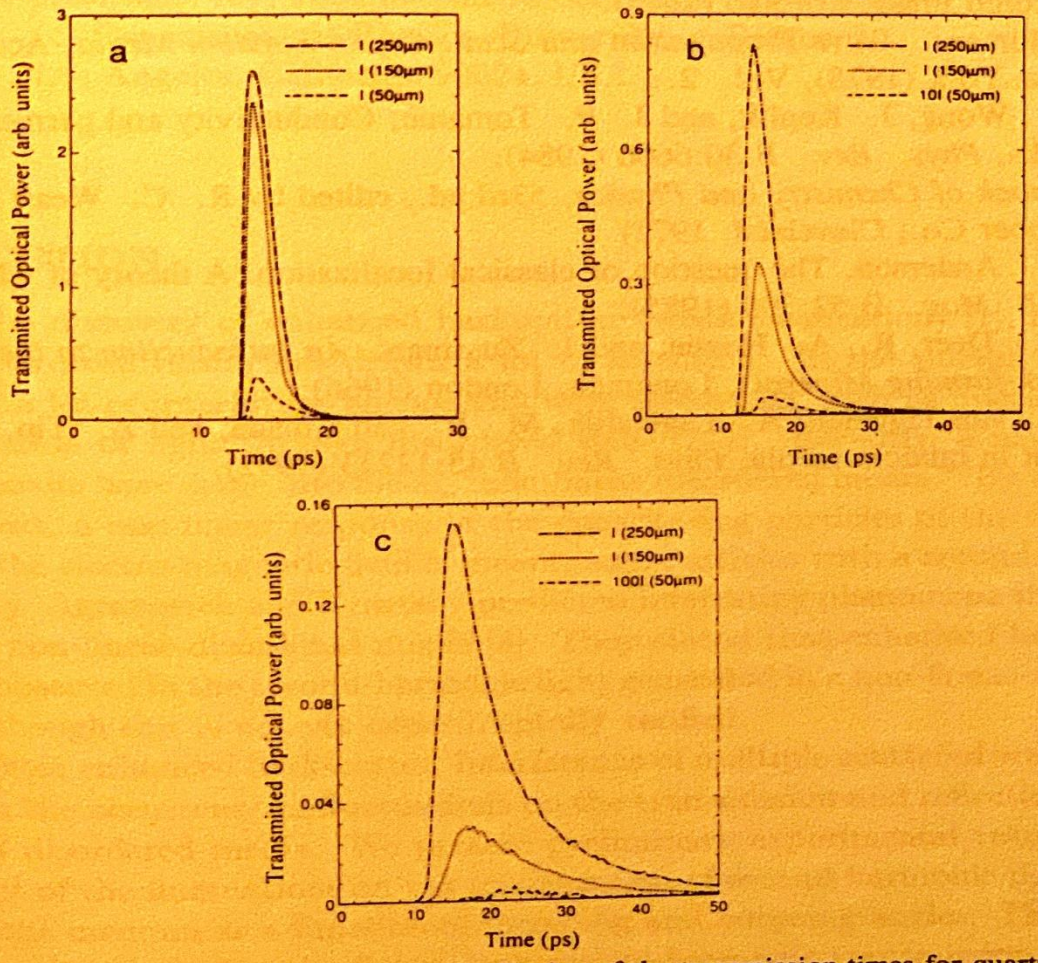


Figure 6. Numerical simulation of the distribution of the transmission times for quartz grain packs of various grain sizes (indicated in the figures), saturated with (a) toluene; (b) water; and (c) air. Normalization is such that for each saturating fluid, the area under a curve equals T/T_0 (T_0 = incident power). The absolute normalization is arbitrary but is the same for each of the three sets of curves (from Ref. 1).

REMARKS

We have discussed a variety of concepts and related experiments in light propagation in porous media. These are intended to serve as a general basis for the development of more detailed and more sophisticated theories and experimental designs. Future investigations in this field may also benefit from multi-wavelength and time-domain studies.

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